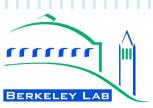


# High-Energy Nuclear Collisions and QCD Phase Structure

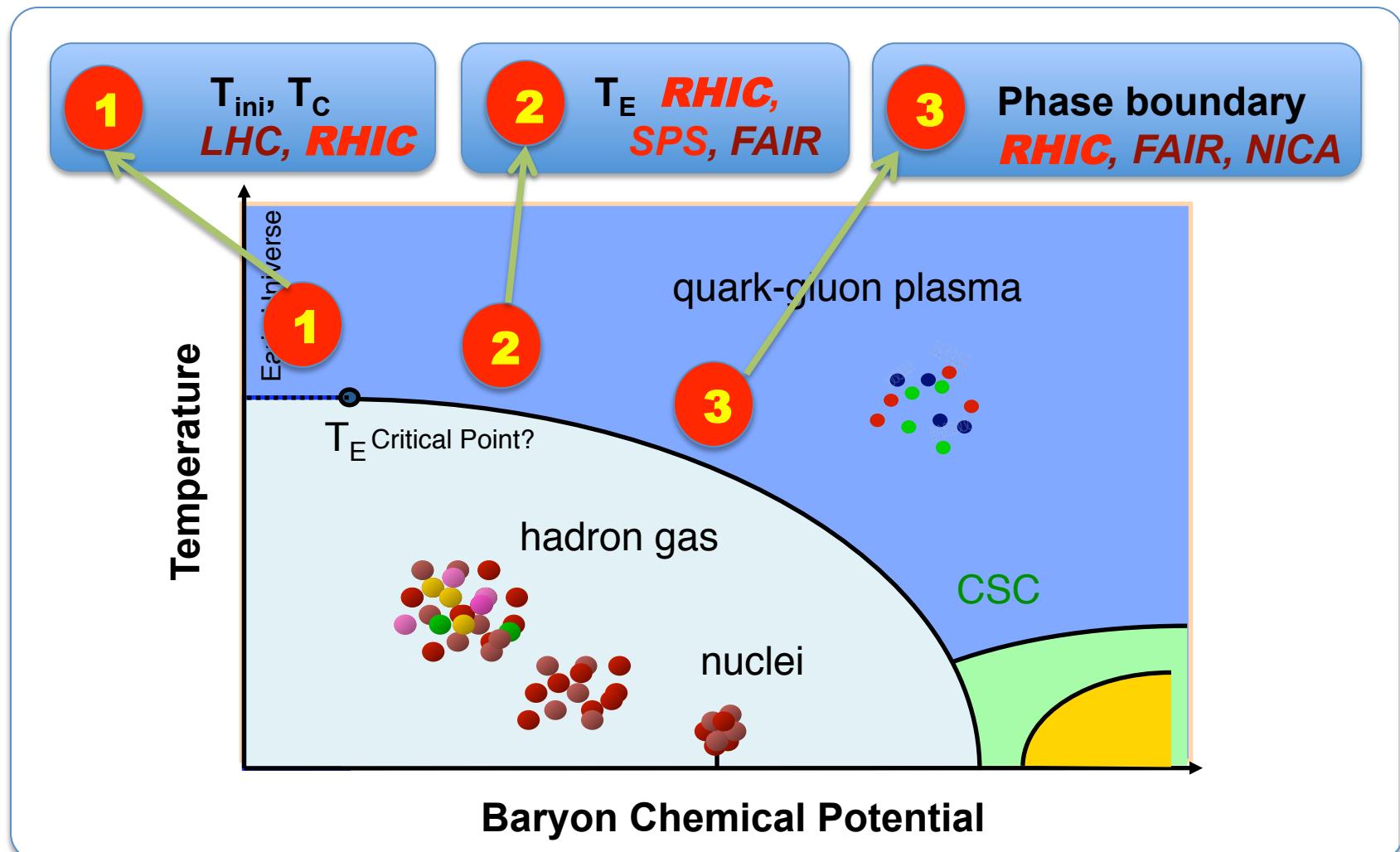
Nu Xu

<sup>(1)</sup> *Nuclear Science Division, Lawrence Berkeley National Laboratory  
Berkeley, USA*

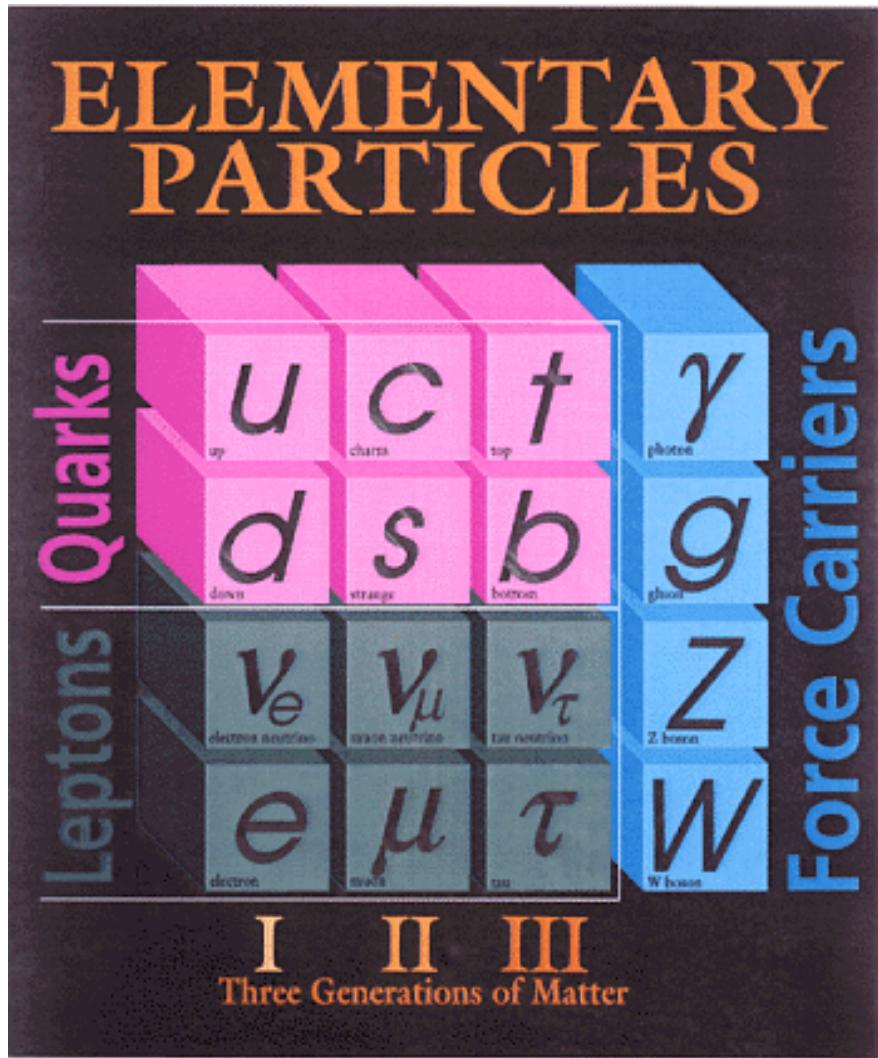
<sup>(2)</sup> *College of Physical Science and Technology, Central China Normal University  
Wuhan, China*



# The QCD Phase Diagram and High-Energy Nuclear Collisions



# Quantum Chromodynamics



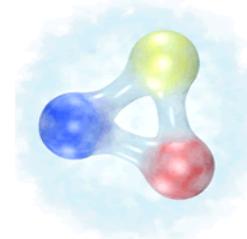
1) Quantum Chromodynamics (QCD) is the established theory of strongly interacting matter.

2) Gluons hold quarks together to form hadrons.

meson



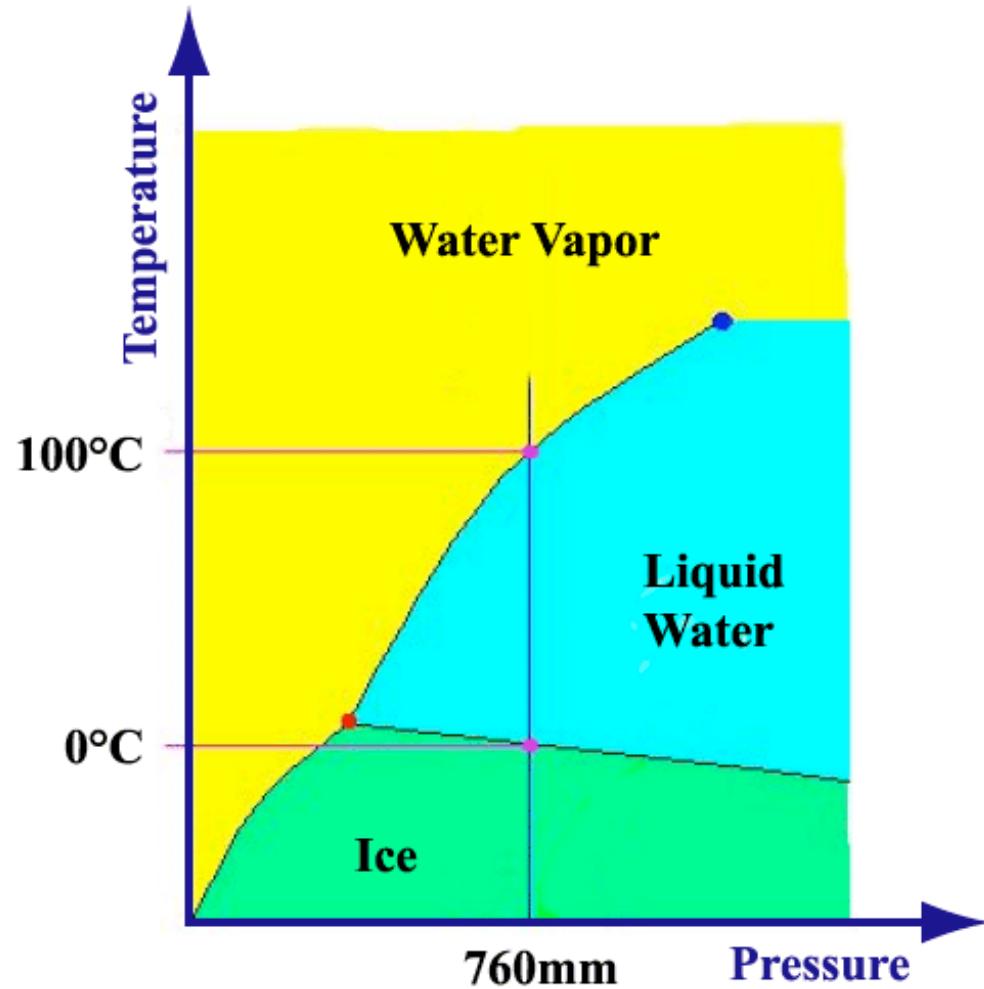
baryon



3) Gluons and quarks, or partons, typically exist in a color singlet state: **confinement**.

Little is known about the structure of the matter.

# Phase Diagram: Water

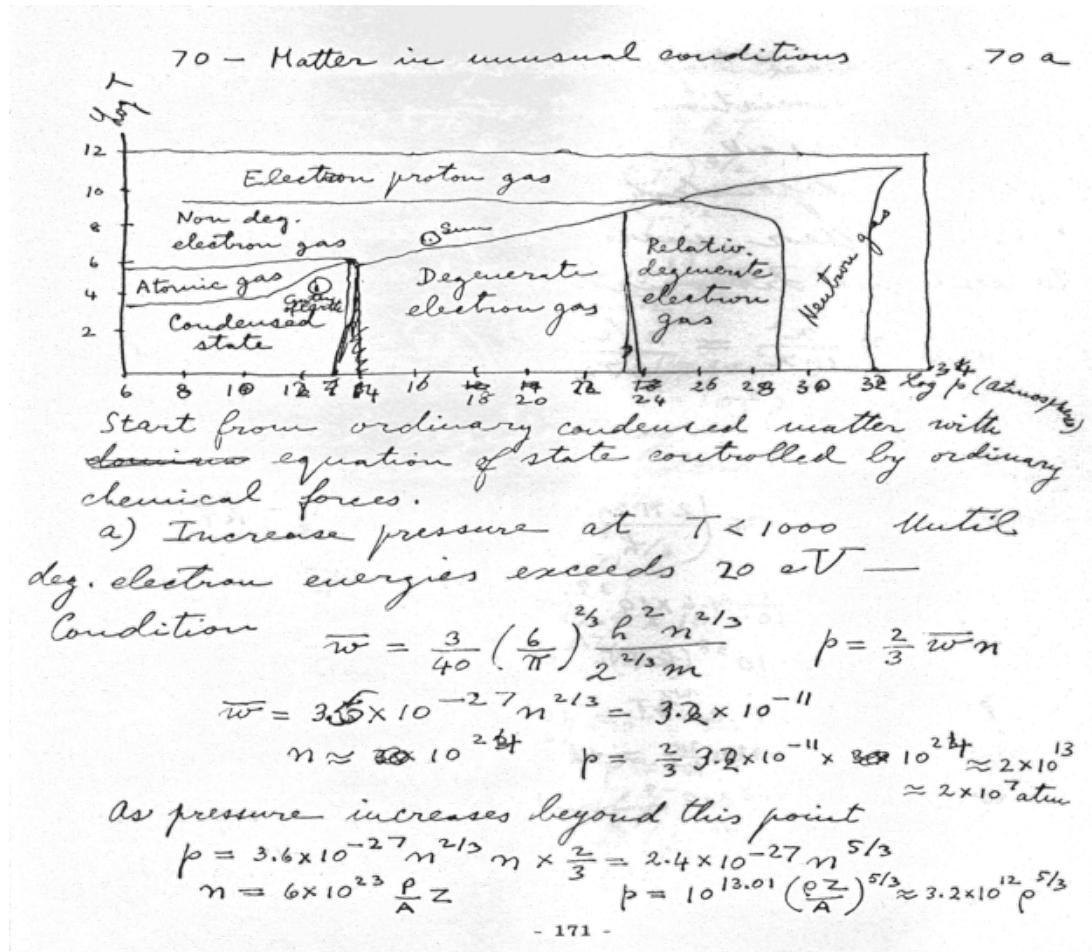


**Phase diagram:** A map shows that, at given degrees of freedom, how matter organize itself under external conditions.

**The QCD Phase diagram:** structure of matter with quark- and gluon-degrees (color degrees) of freedom.

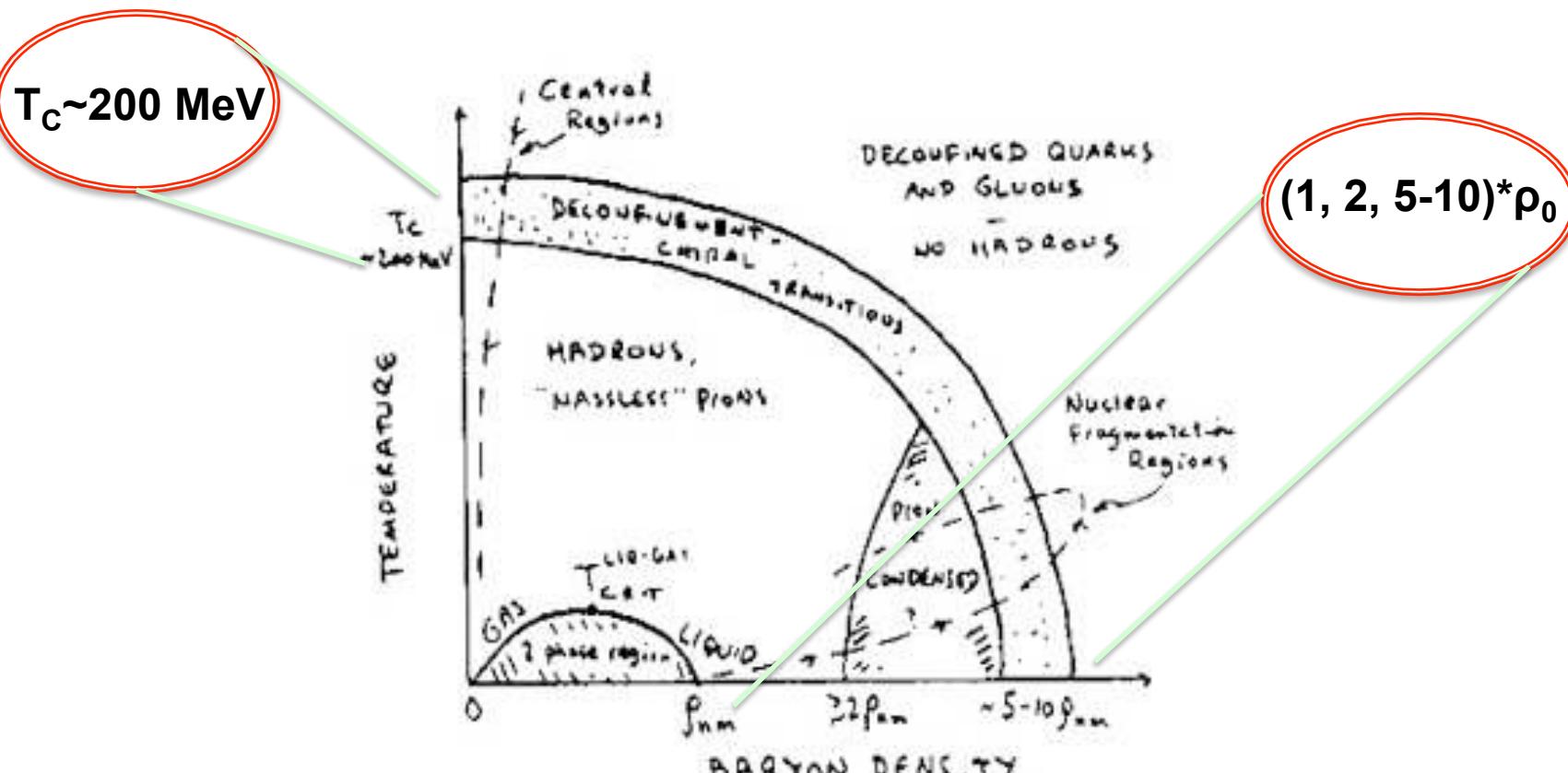
# QCD Phase Diagram (1953)

E. Fermi: "Notes on Thermodynamics and Statistics" (1953)



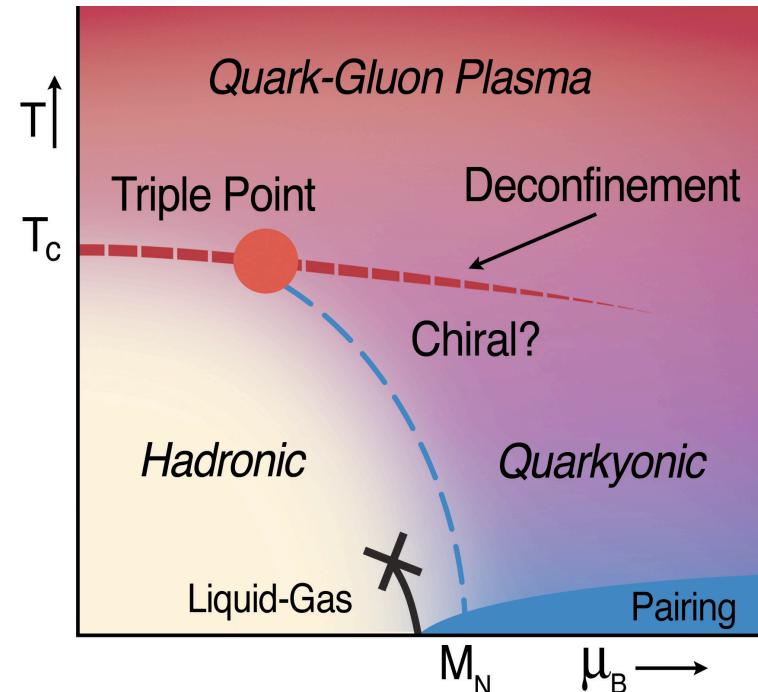
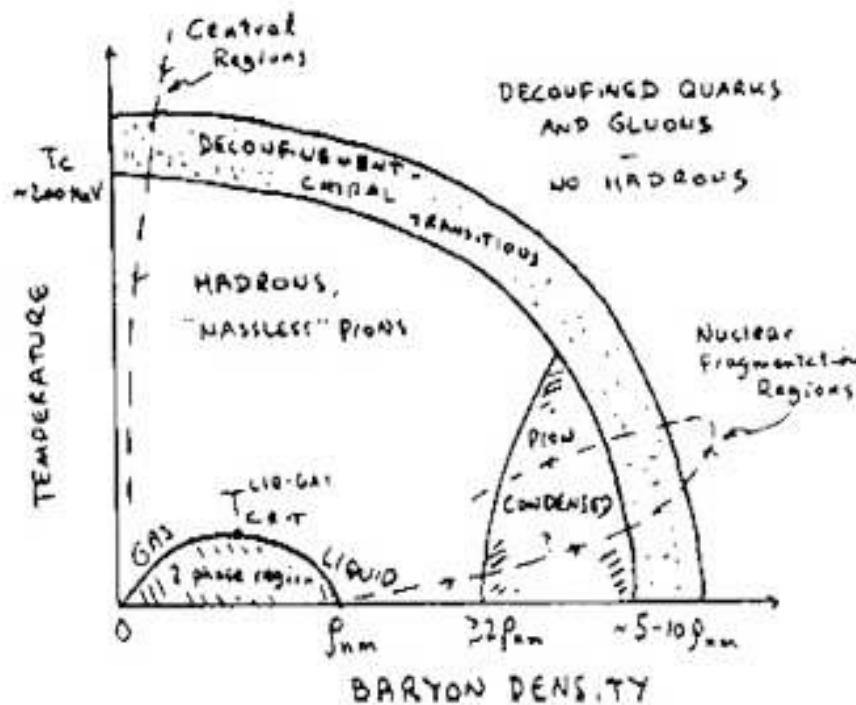
# QCD Phase Diagram 1983

1983 US Long Range Plan - by Gordon Baym



# QCD Phase Diagram (2009)

1983 US Long Range Plan - by Gordon Baym



nucl-th: 0907.4489, NPA830,709(09) L. McLerran

nucl-th 0911.4806: A. Andronic, D. Blaschke, P. Braun-Munzinger, J. Cleymans, K. Fukushima, L.D. McLerran, H. Oeschler, R.D. Pisarski, K. Redlich, C. Sasaki, H. Satz, and J. Stachel

**Systematic experimental measurements ( $E_{beam}$ ,  $A$ ):**  
**Extract numbers that is related to the QCD phase diagram!**



# Outline

---



(1) Introduction

(2) STAR experiment

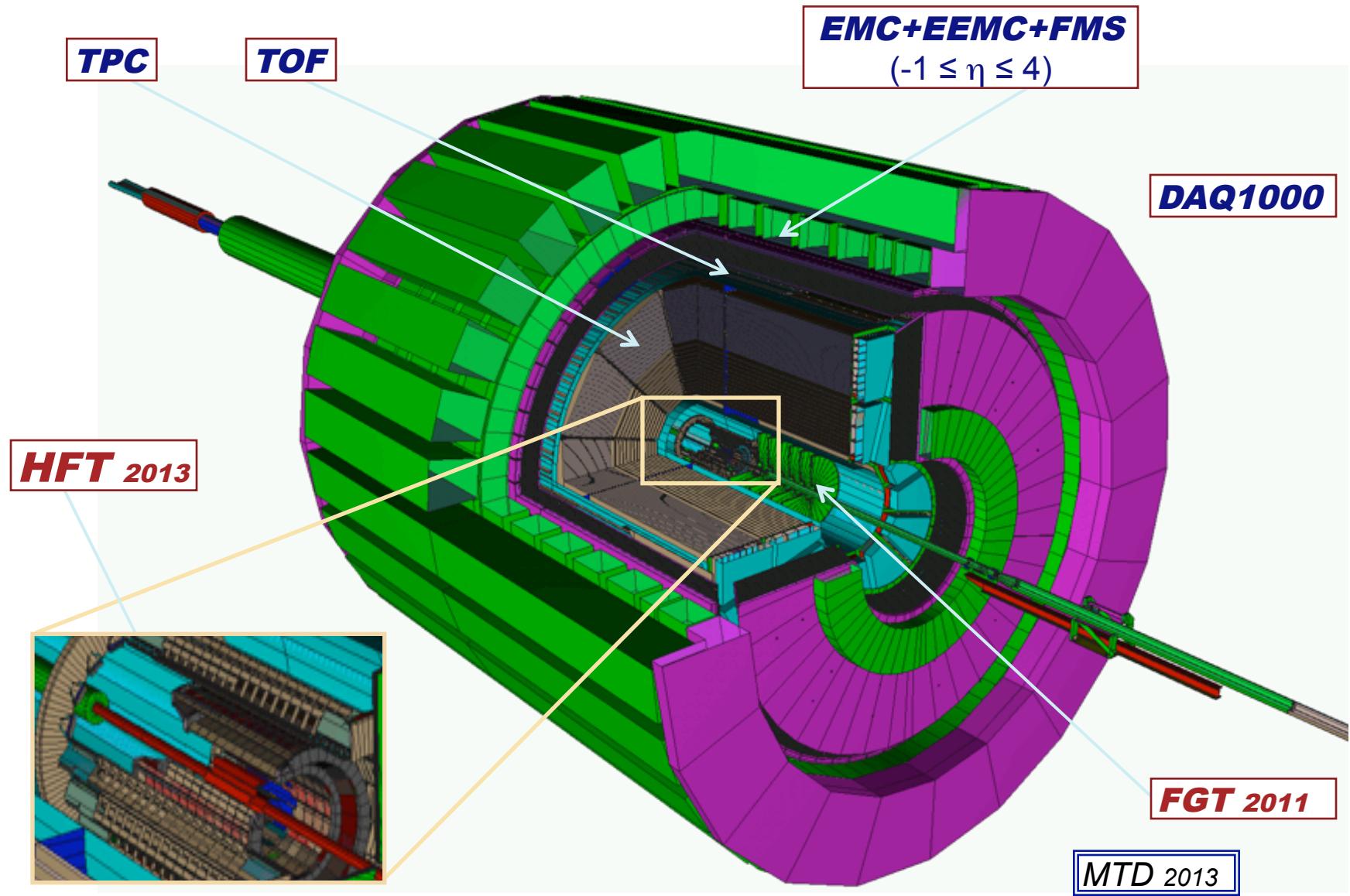
(3) Observables and recent results

Three Examples: (i)  $\nu_2$ ; (ii) S, K; (iii) *di-electron*

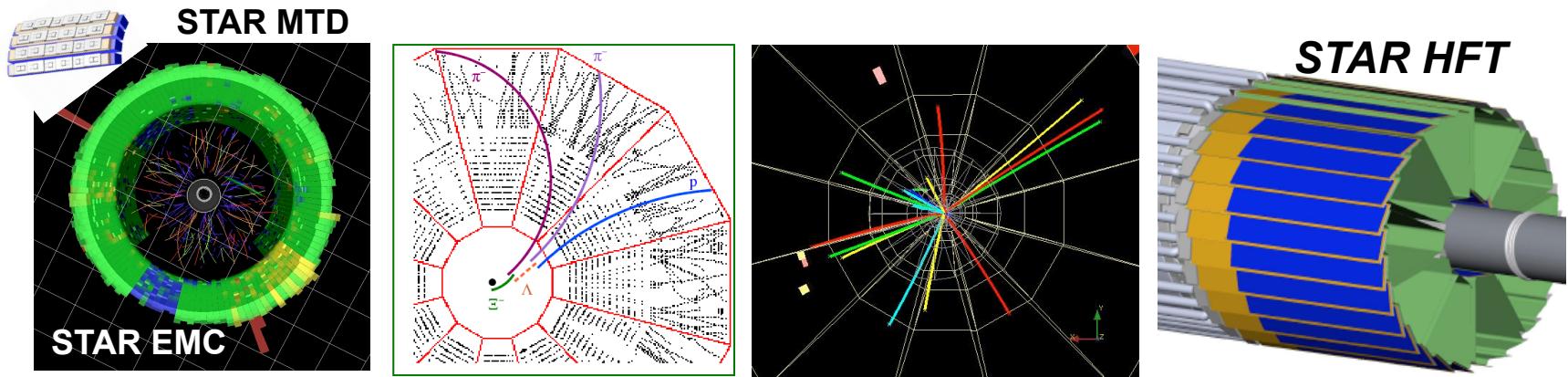
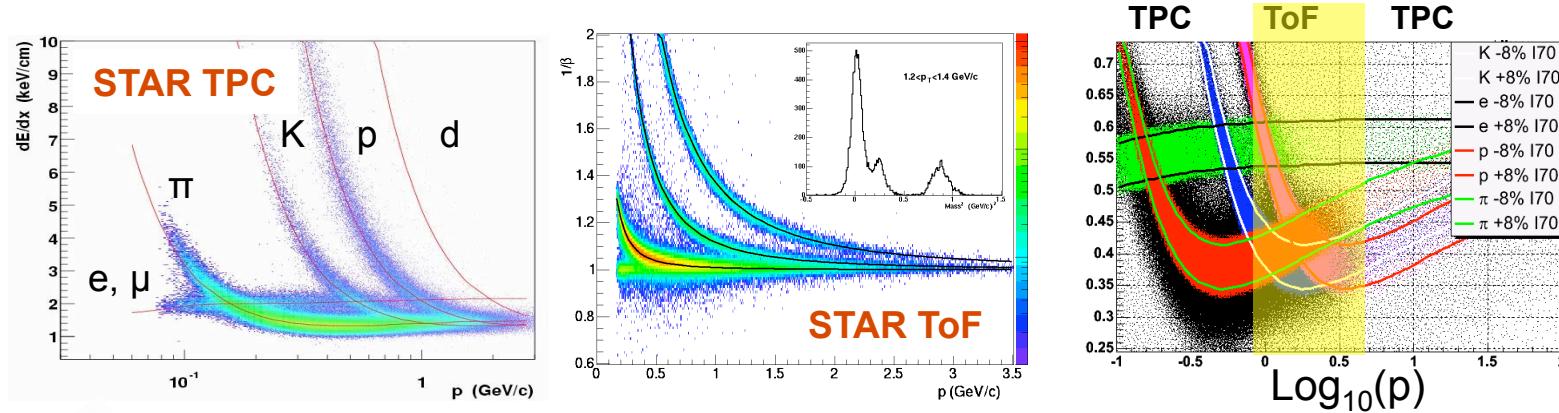
(4) Outlook



# STAR Detectors *Fast and Full azimuthal particle identification*



# Particle Identification at STAR



Neutral particles

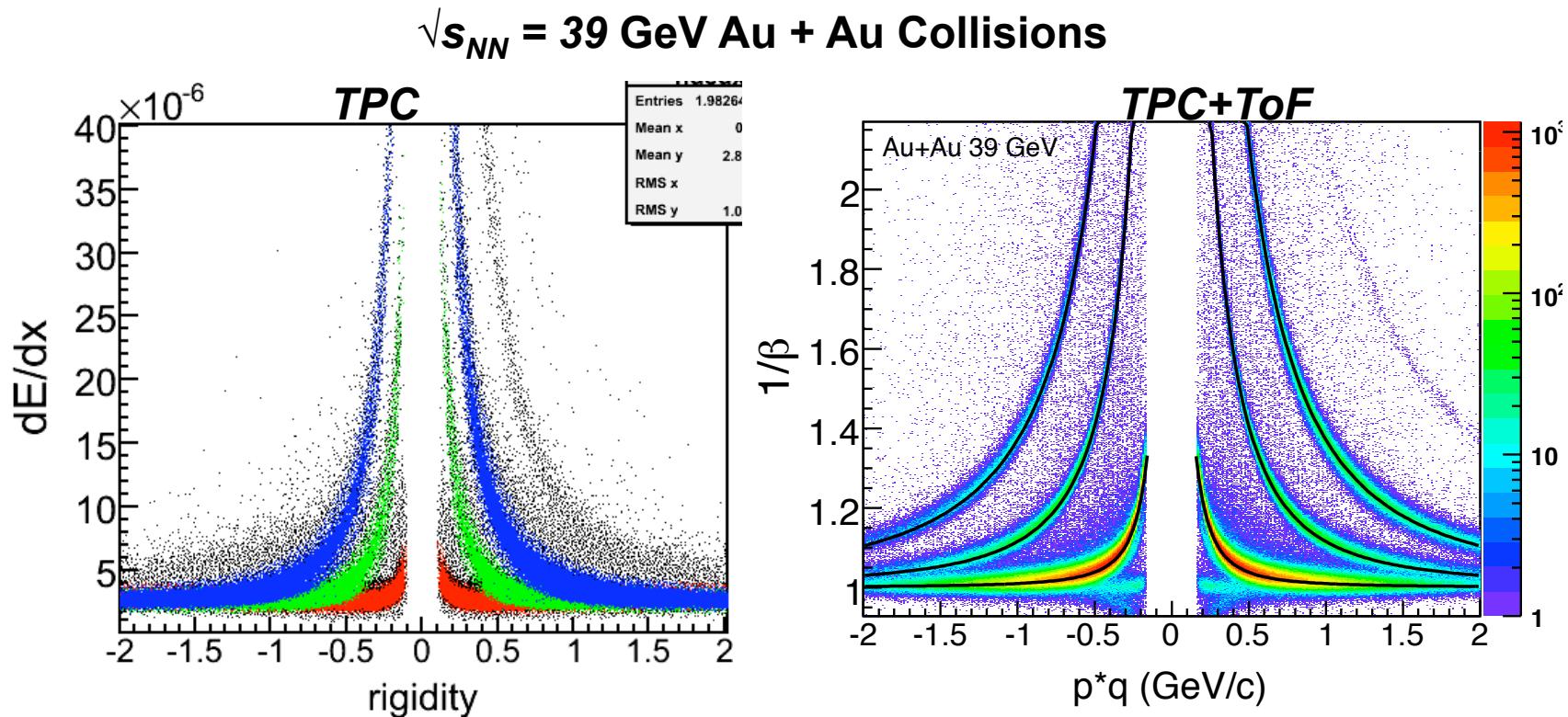
Strange  
hyperons

Jets

Heavy Quark  
Hadrons

***Multiple-fold correlations among the identified particles!***

# TOF Performance (2010)



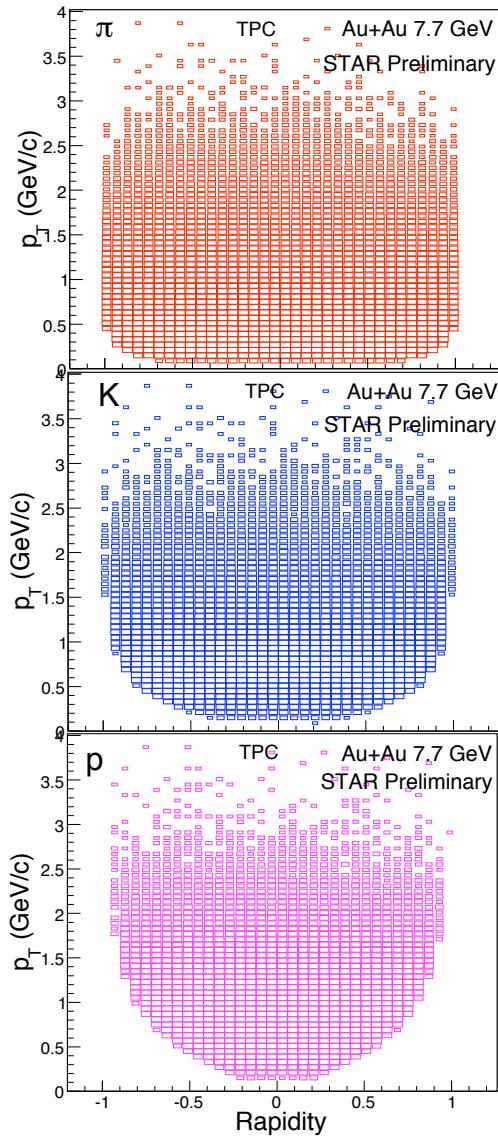
| Beam Energy      | Timing Resolution | Remarks   |
|------------------|-------------------|---|
| 200 (GeV)        | 85 (ps)           | At 39 GeV, using a new calibration scheme without information of start time from VPD, 87 ps of timing resolution has been achieved. |
| 62.4 (GeV)       | 90 (ps)           |   |
| 39 (GeV)         | 85 (ps)           |   |
| 11.5 & 7.7 (GeV) | $\sim 80$ (ps)    |   |



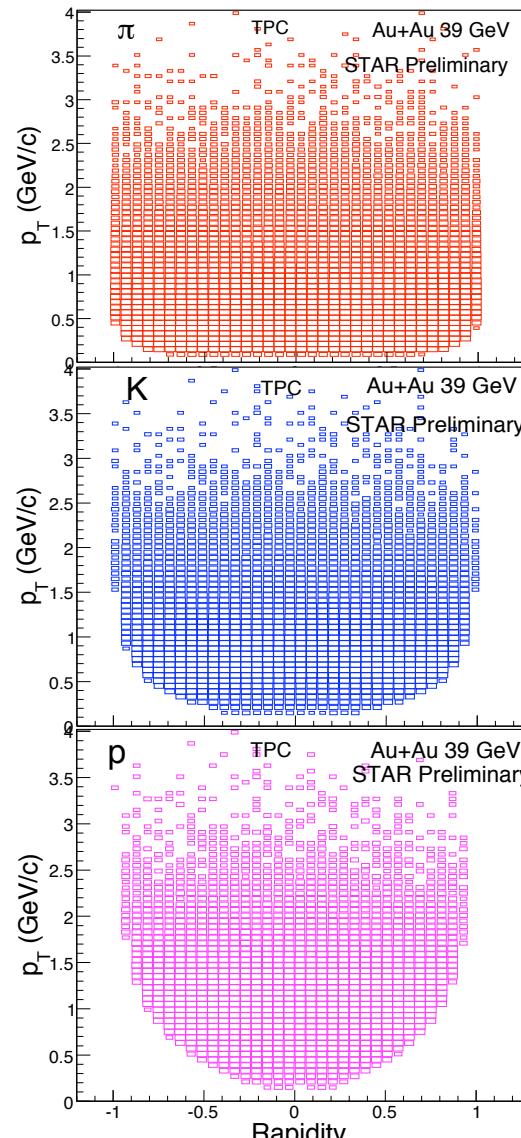
# PID: 7.7, 39, 200 GeV ( $p^\pm$ , $K^\pm$ , $p$ )



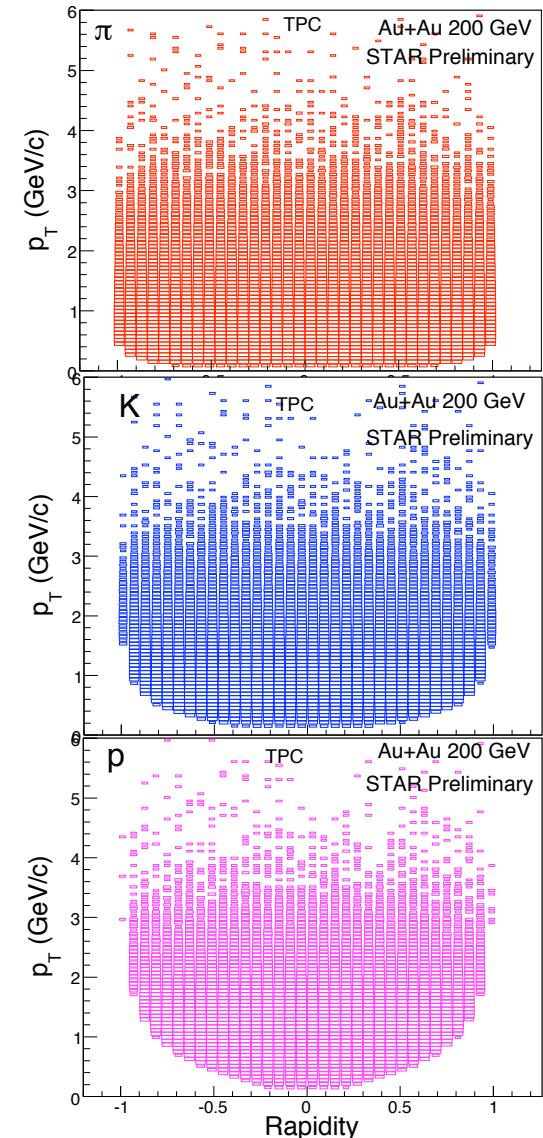
Au+Au at 7.7 GeV



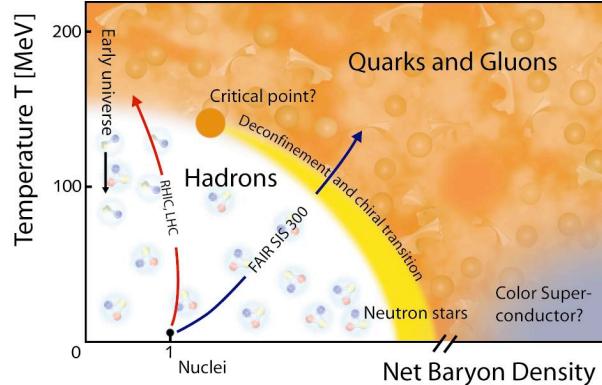
Au+Au at 39 GeV



Au+Au at 200 GeV



# STAR Physics Focus

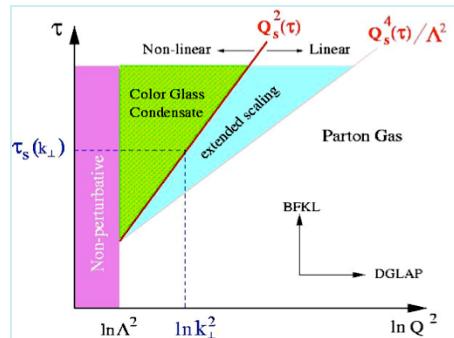


## 1) At 200 GeV top energy

- Study **medium properties, EoS**
- pQCD in hot and dense medium

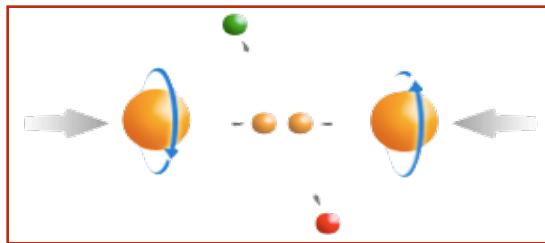
## 2) RHIC beam energy scan (BES)

- Search for the  **$QCD$  critical point**
- Chiral symmetry restoration



## Forward program

- Study low-x properties, initial condition, search for **CGC**
- Study elastic and inelastic processes in pp2pp



## Polarized $p+p$ program

- Study **proton intrinsic properties**



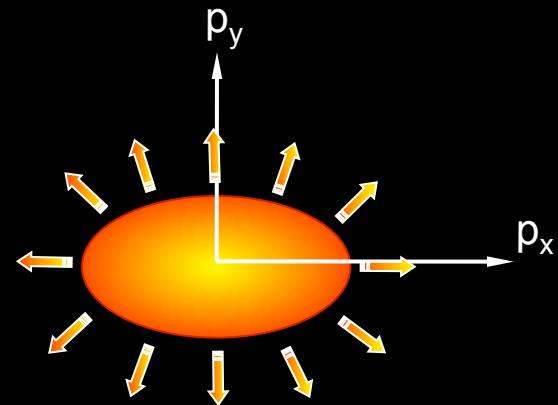
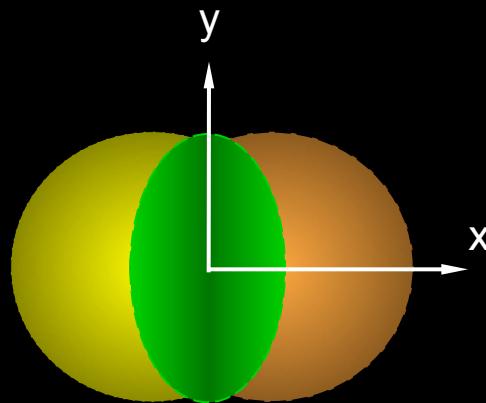
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Example I:

# Partonic Collectivity

# Anisotropy Parameter $v_2$

coordinate-space-anisotropy  $\Leftrightarrow$  momentum-space-anisotropy

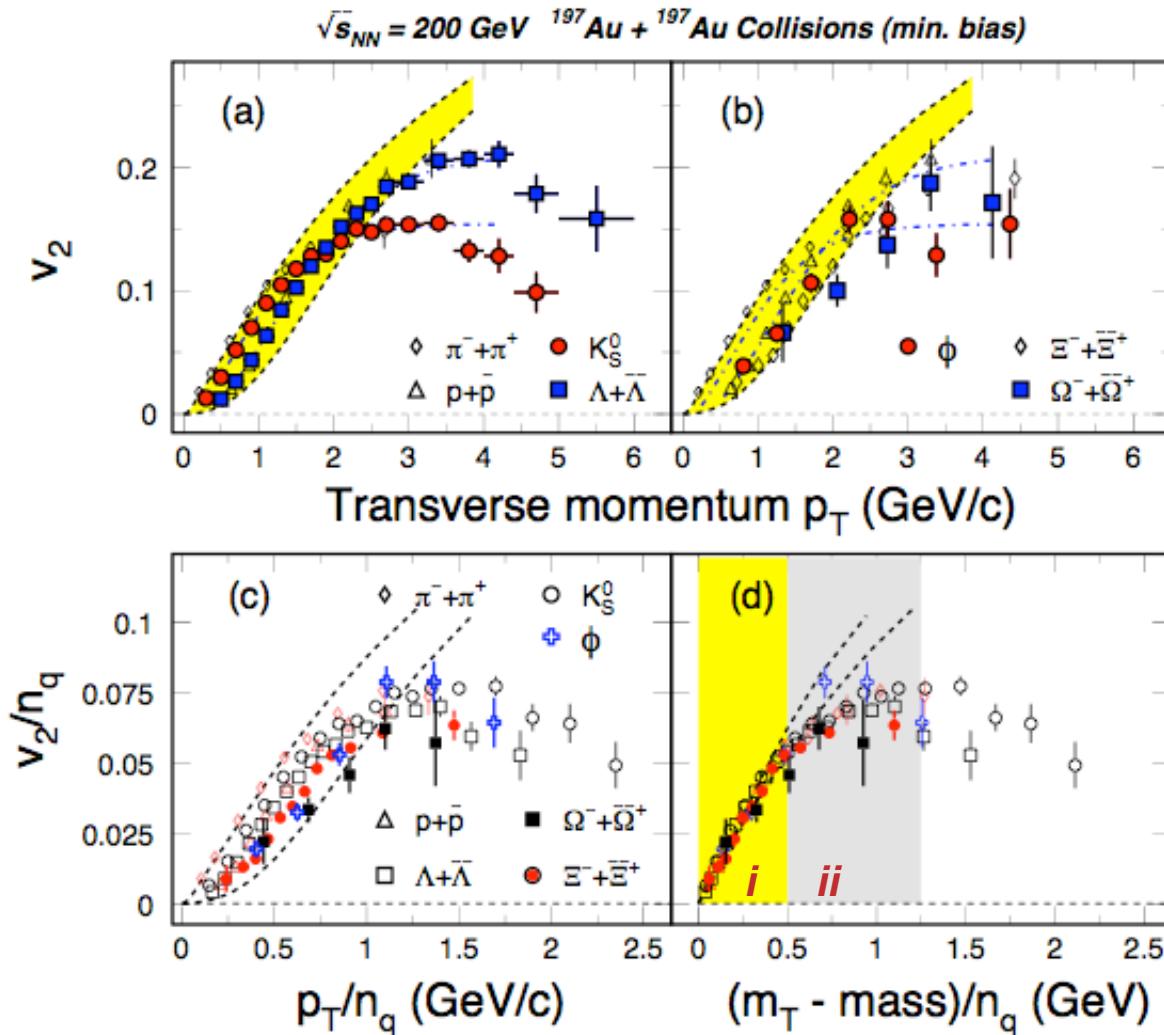


$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

$$v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1} \left( \frac{p_y}{p_x} \right)$$

Initial/final conditions, EoS, degrees of freedom

# Collectivity, De-confinement at RHIC



- $v_2$  of light hadrons and multi-strange hadrons
- scaling by the number of quarks

At RHIC:

- ➡  **$n_q$ -scaling**  
novel hadronization process
- ➡ **Partonic flow**  
De-confinement

**PHENIX**: *PRL* **91**, 182301(03)

**STAR**: *PRL* **92**, 052302(04), **95**, 122301(05)  
*nucl-ex*/0405022, QM05

S. Voloshin, *NPA* **715**, 379(03)

Models: Greco et al, *PRC* **68**, 034904(03)

Chen, Ko, *nucl-th*/0602025

Nonaka et al. *PLB* **583**, 73(04)

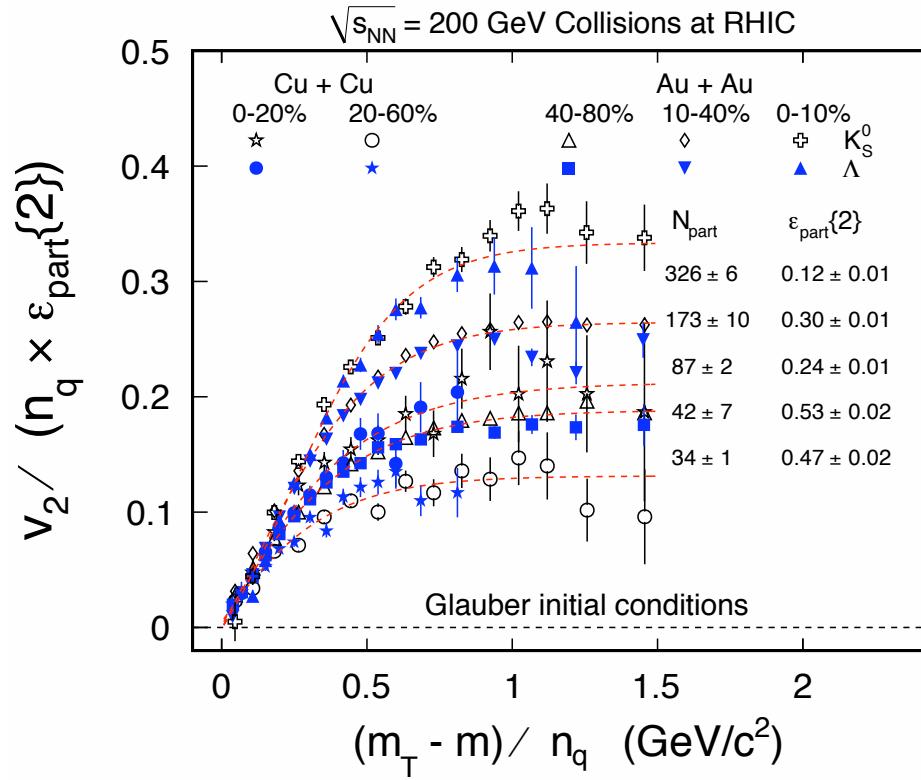
X. Dong, et al., *Phys. Lett.* **B597**, 328(04).

....

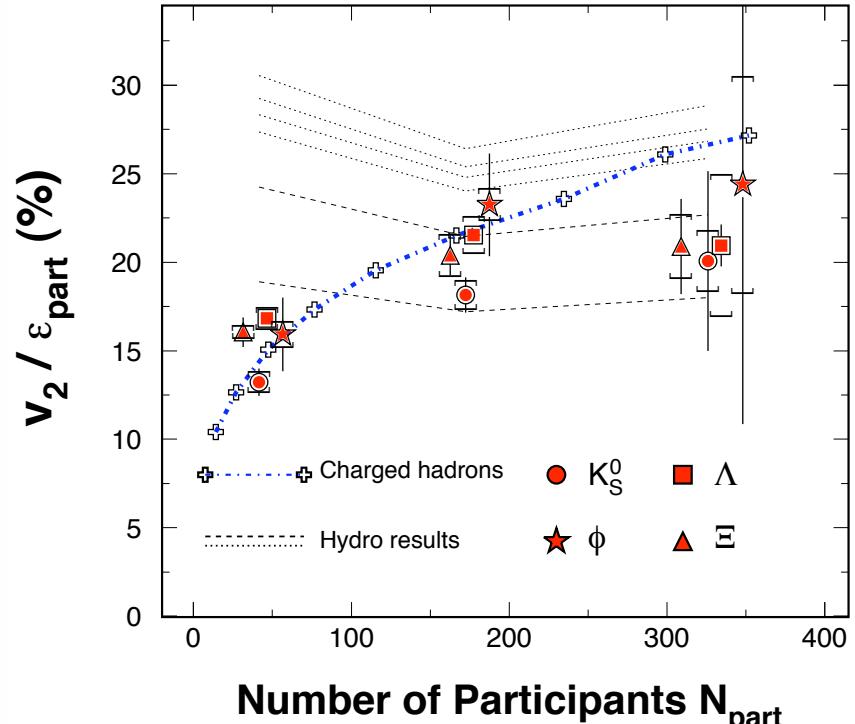
# System Size Driven Collectivity

200 GeV Au+Au Collisions at RHIC

*Phys. Rev. C81*, 44902(2010)

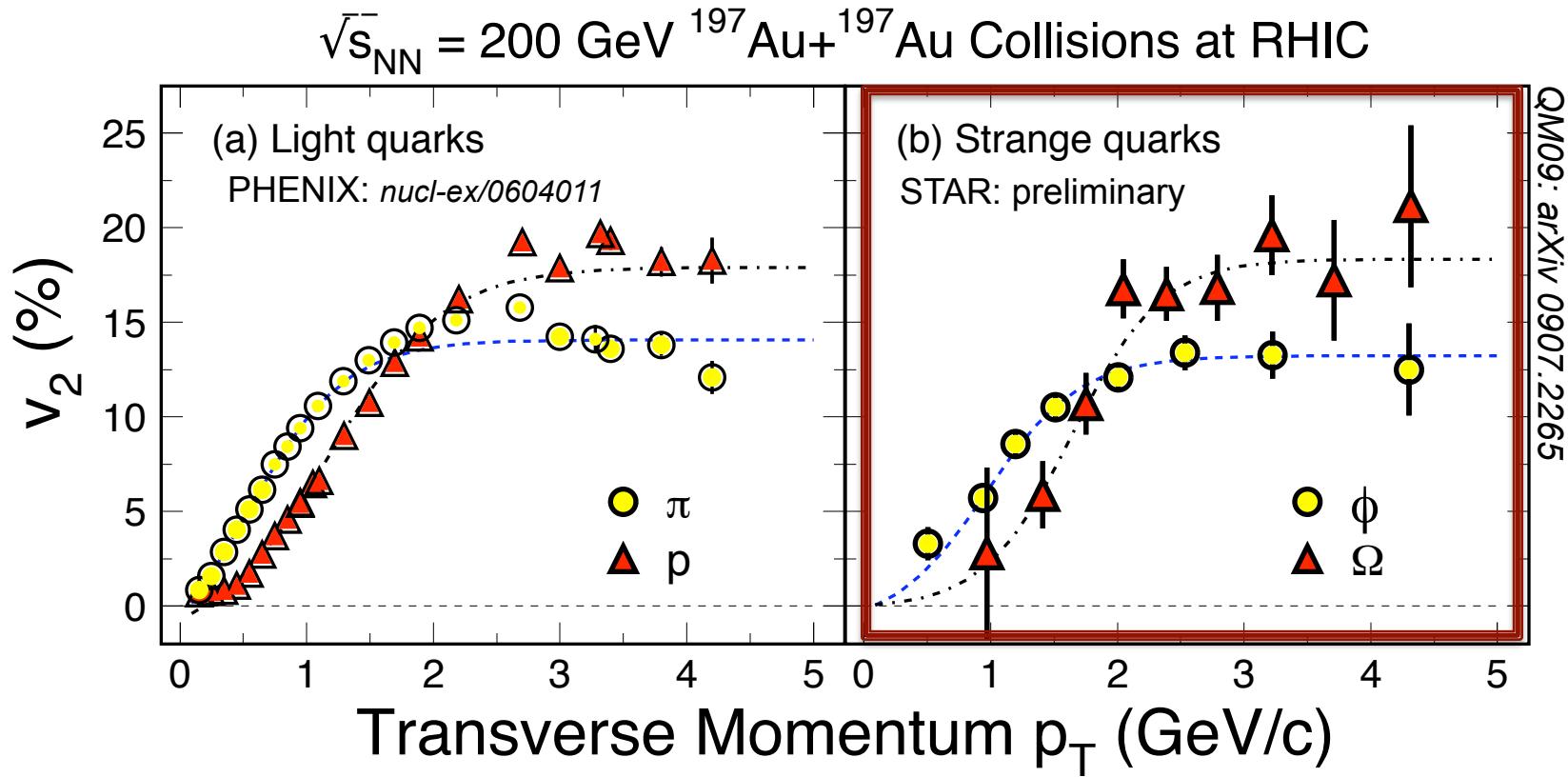


*Phys. Rev. C77*, 54901(2008)



**Collectivity:** Driven by number of participants  
**Thermalization:** ?

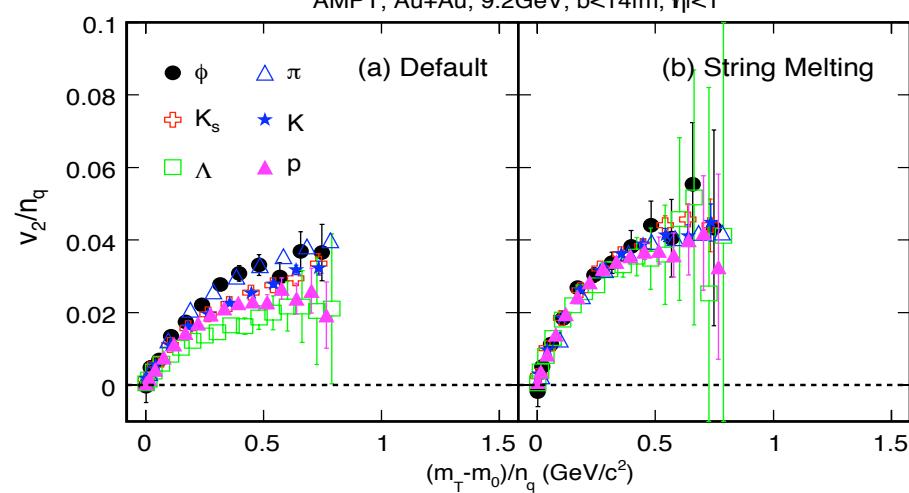
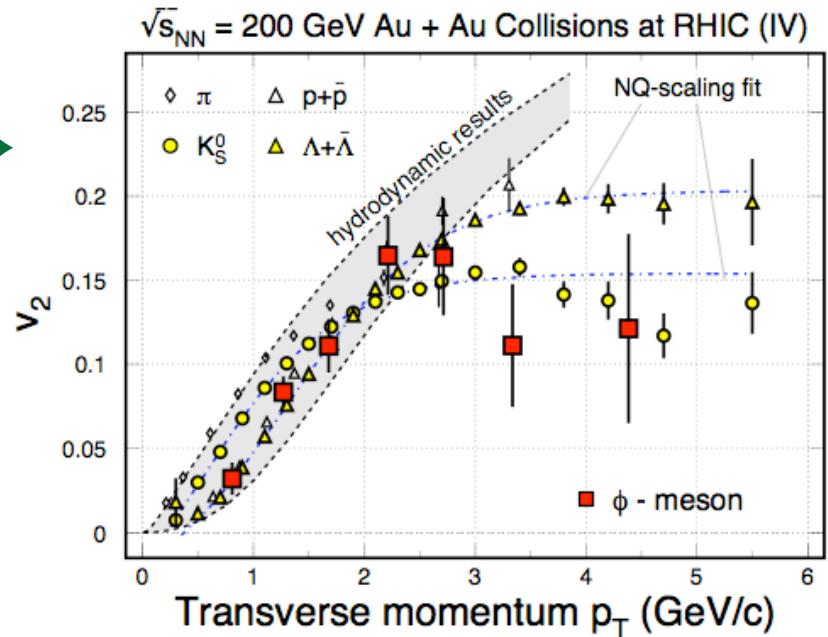
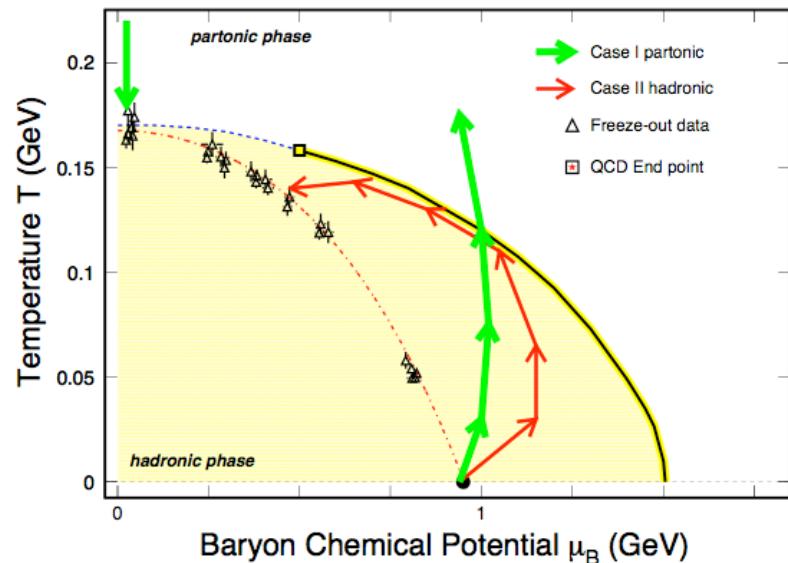
# Partonic Collectivity at RHIC



Low  $p_T$  ( $\leq 2 \text{ GeV}/c$ ): hydrodynamic mass ordering  
 High  $p_T$  ( $> 2 \text{ GeV}/c$ ): number of quarks ordering  
 s-quark hadron: smaller interaction strength in hadronic medium  
 light- and s-quark hadrons: similar  $v_2$  pattern

=> **Partonic Collectivity at RHIC !**

# Observable: Quark Scaling



- $m_\phi \sim m_p \sim 1 \text{ GeV}$
- $S\bar{S} \Rightarrow \phi$  not  $K^+K^- \Rightarrow \phi$
- $\sigma_{\phi h} \ll \sigma_{p\pi, \pi\pi}$

In the hadronic case:

- (i) No number of quark scaling
- (ii) Very small value of  $\phi v_2$ !



---

## Example II:

# High Order Correlation Functions



# Correlations, Susceptibilities, Kurtosis



$$\delta N = N - \langle N \rangle$$

$$\langle (\delta N)^2 \rangle \approx \xi^2, \quad \langle (\delta N)^3 \rangle \approx \xi^{4.5}$$

$$\langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2 \approx \xi^7$$

M. A. Stephanov, PRL. 102, 032301 (09)

$$S = \frac{\langle (\delta N)^3 \rangle}{\langle (\delta N)^2 \rangle^{3/2}}$$

$$K = \frac{\langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2}{\langle (\delta N)^2 \rangle^2} = \frac{\chi_x^4}{\chi_x^2}$$

R.V. Gavai and S. Gupta: 1001.2796.  
F. Karsch and K. Redlich, arXiv:1007.2581

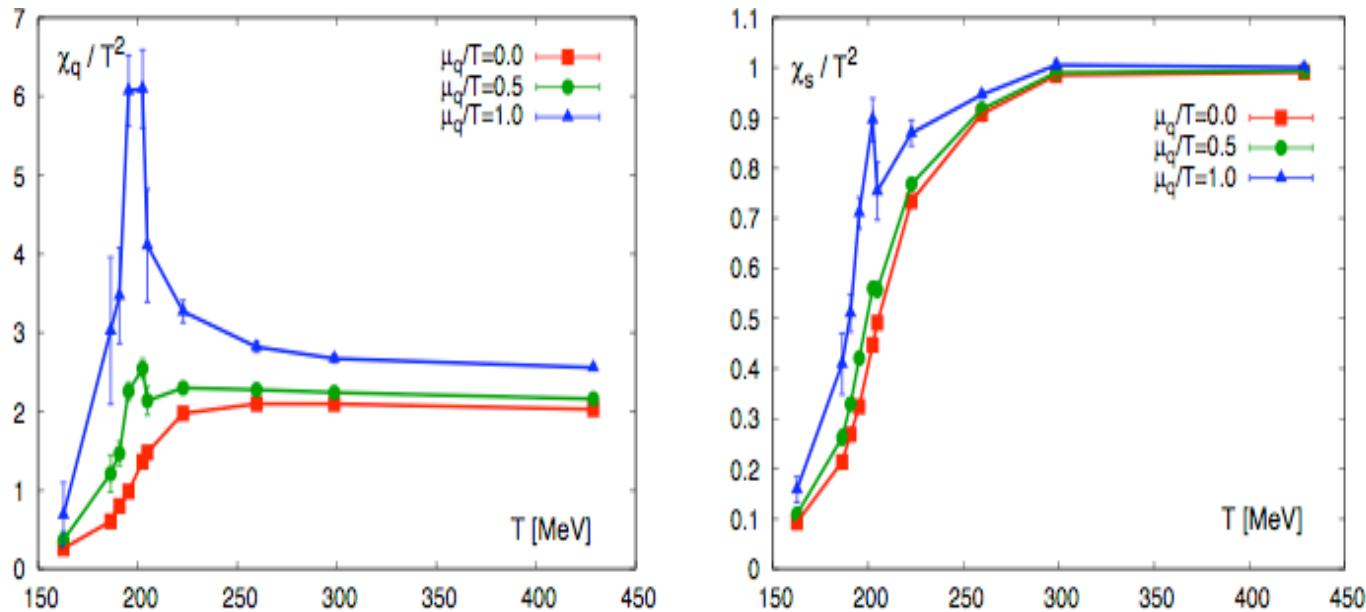
Higher order correlations are correspond to higher power of the correlation length of the system: **more sensitive to critical phenomena.**

**S**kewness: Symmetry of the correlation function.

**K**urtosis: Peakness of the correlation function. *Connection to thermodynamics,  $\chi_x$ .*

**S & K** observables:  
total charge, total protons,  
net-p, net-Q

# High Order Correlations



Event by event:

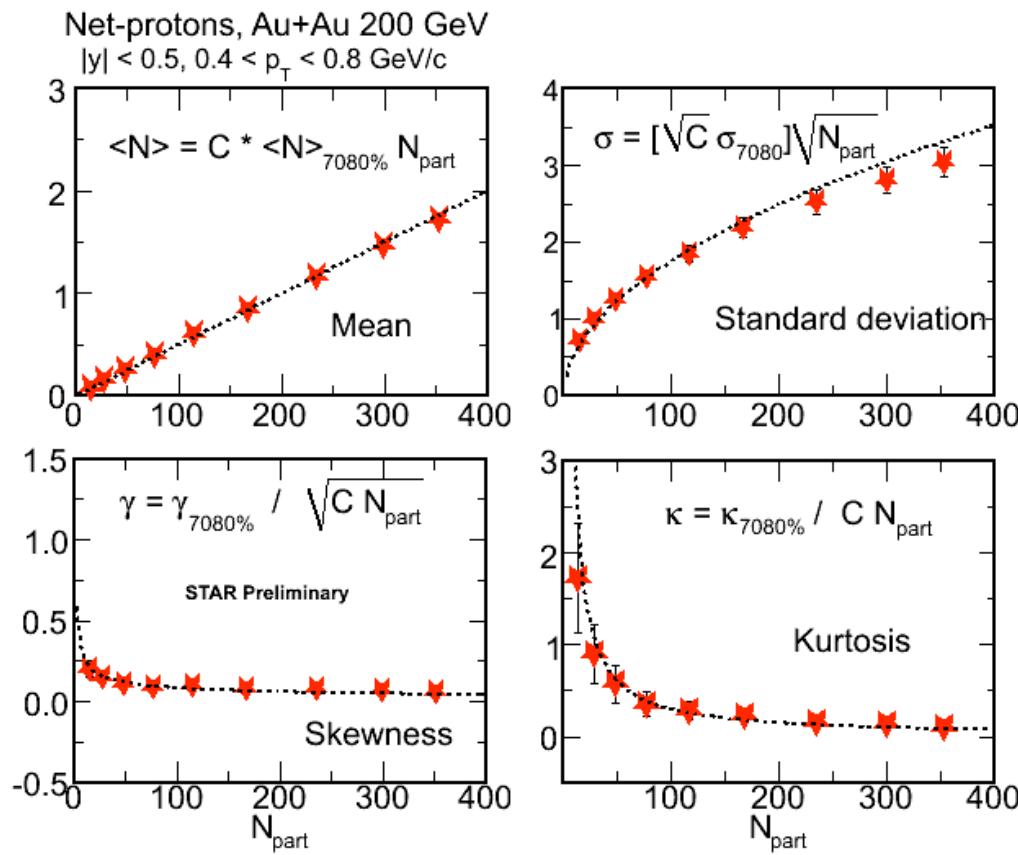
1. net-proton Kurtosis  $K_p(E)^*$
2. two proton correlation functions  $C_2(E)$
3. ratio of the d/p
4. ratio of K/p

$$K_p = \frac{\langle N_p^4 \rangle - 3\langle N_p^2 \rangle^2}{\langle N_p^2 \rangle}$$

\* Gavai and Gupta, 03, 05; Gupta 0909.4630  
 M. Cheng et al. 08  
 Gupta, Karsch, Stephanov, INT, 08

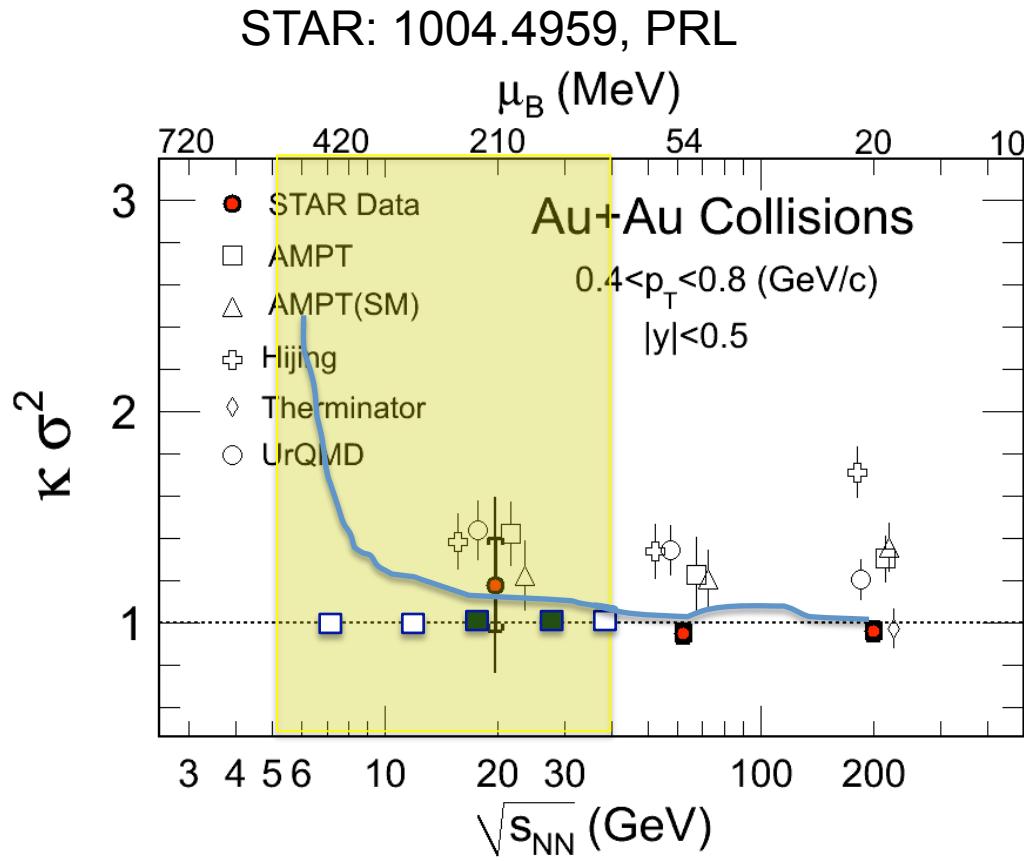
# High Moment Analysis at STAR

STAR: 1004.4959, PRL



- 1) High moments are more sensitive to critical point related fluctuation.
- 2) The 4<sup>th</sup> moment, Kurtosis, is *directly related* to the corresponding thermodynamic quantity: susceptibility for conserved quantum numbers such as Baryon number, charge, strangeness...

# Net-proton High Moments



***Estimated errors in Au+Au collision :***

- Run 10: 7.7, 11.5, 39 GeV
- Run 11: 18, 27 GeV

- 1) STAR results\* on net-proton high moments for Au+Au collisions at  $\sqrt{s_{NN}} = 200, 62.4$  and  $19.6$  GeV.
- 2) Sensitive to critical point\*\*:  
 $\langle (\delta N)^2 \rangle \approx \xi^2$ ,  $\langle (\delta N)^3 \rangle \approx \xi^{4.5}$ ,  $\langle (\delta N)^4 \rangle \approx \xi^7$
- 3) Direct comparison with Lattice results\*\*:  
 $S * \sigma \approx \frac{\chi_B^3}{\chi_B^2}$ ,  $\kappa * \sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$
- 4) Extract susceptibilities and freeze-out temperature. An independent test on thermal equilibrium in heavy ion collisions.

\* STAR: 1004.4959, accepted by PRL(2010).

\*\* M. Stephanov: PRL, 102, 032301(2009).

\*\*\* R.V. Gavai and S. Gupta: 1001.2796.

F. Karsch and K. Redlich, arXiv:1007.2581

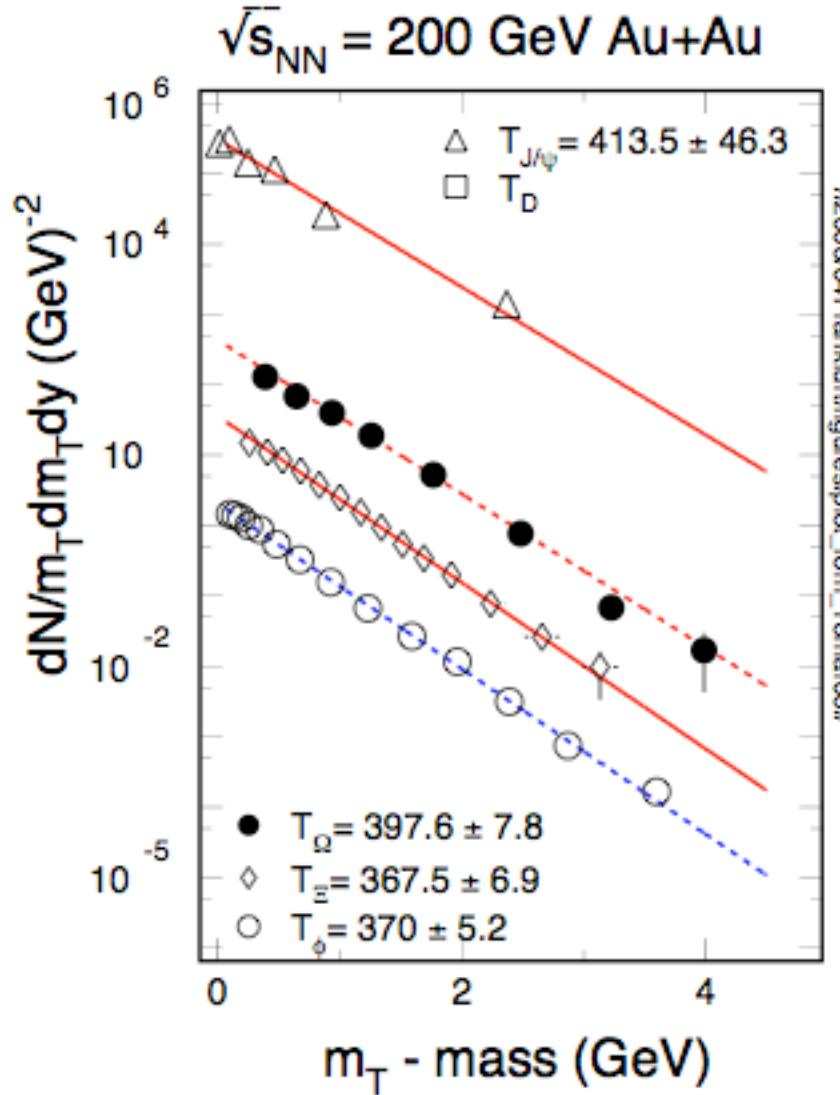


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## Example III:

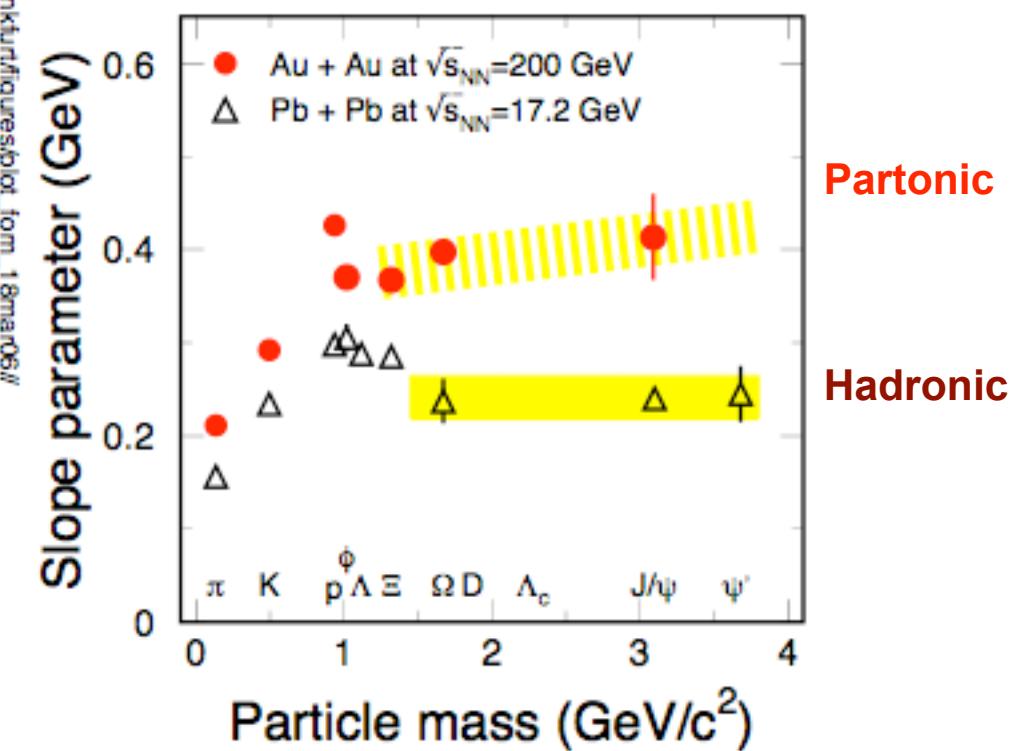
# Slope Parameters of Hadrons and Leptons

# Slope Parameter Systematics

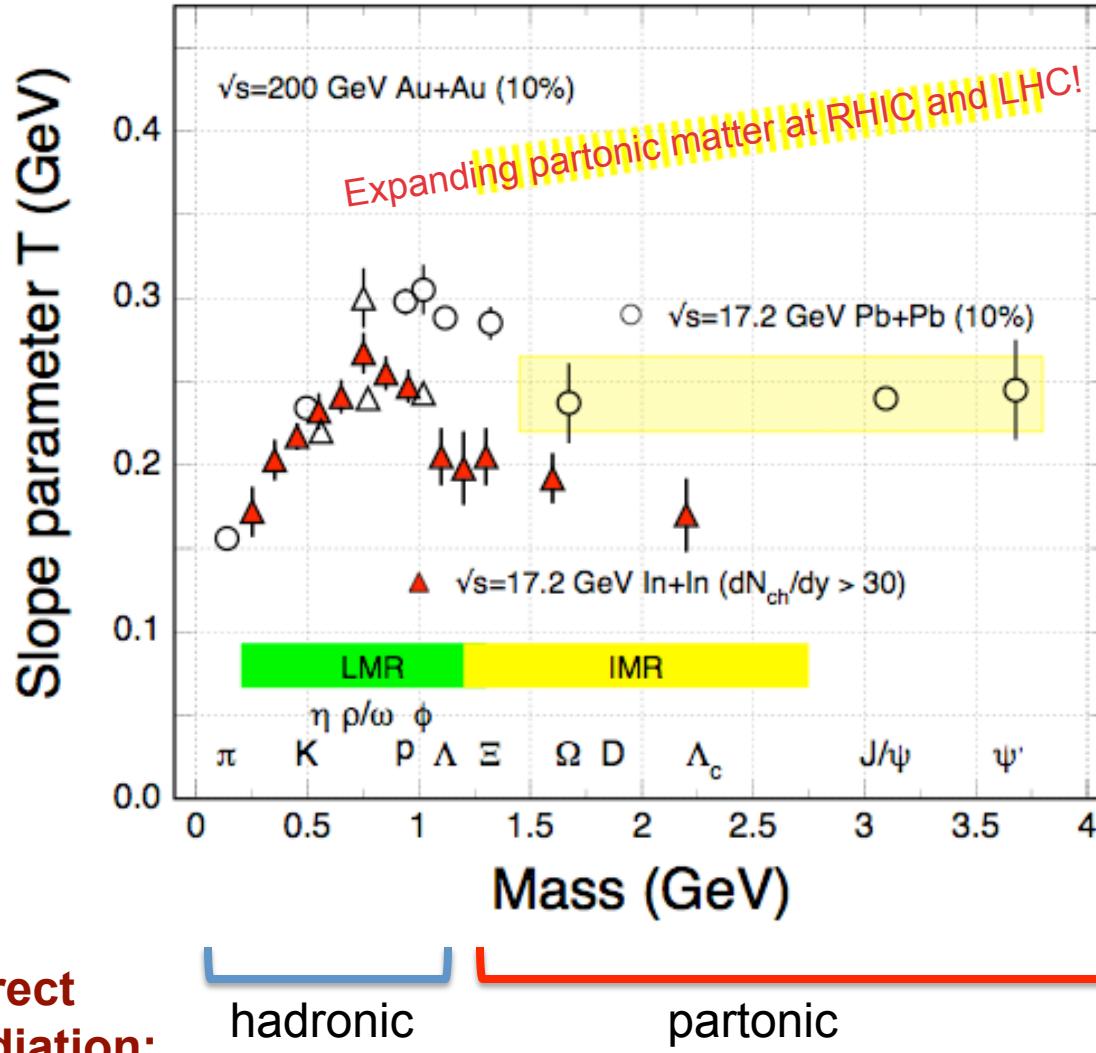


$$m_T = \sqrt{p_T^2 + m^2}$$

$$f \propto \exp(-m_T/T_{slope})$$



# Direct Radiation Measurements



STAR already started its ***di-electron*** measurements!

Di-leptons allow us to measure the direct radiation from the matter with partonic degrees of freedom, no hadronization!

- Low mass region:

$$\rho, \omega, \phi \Rightarrow e^-e^+$$

$$m_{inv} \Rightarrow e^-e^+$$

**medium effect**

**Chiral symmetry(?)**

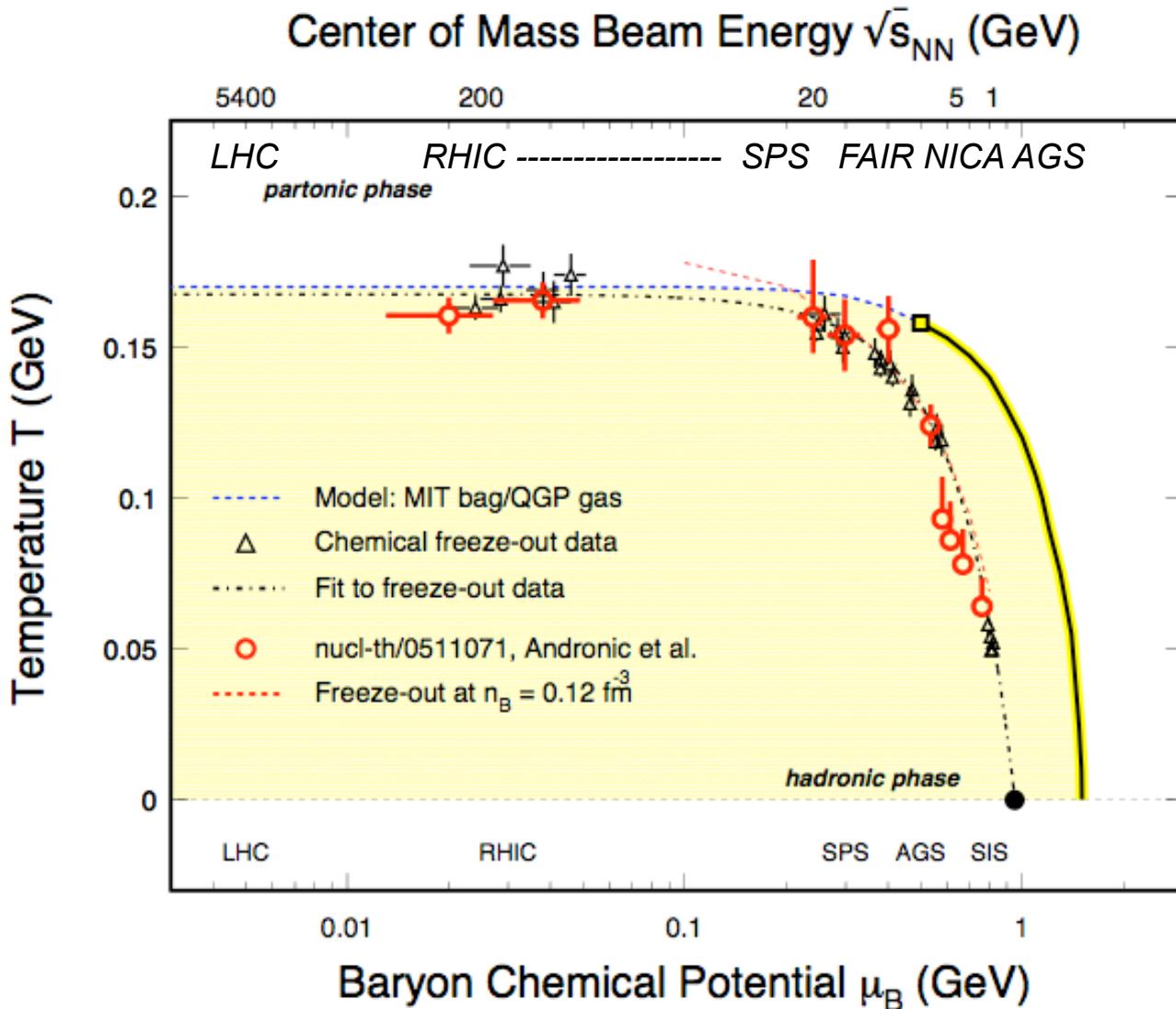
- Intermediate region:

$$J/\psi \Rightarrow e^-e^+$$

$$m_{inv} \Rightarrow e^-e^+$$

**Direct radiation**

# QCD Phase Diagram



$T_{ch} \sim T_c$  (LGT) at RHIC.  
*\*Thermalization has been assumed!*

LHC:  $T_i$ ,  $T_c$

RHIC & SPS:  $T_c$ ,  $T_E$ ,  
 and phase boundary

FAIR & NICA: Details  
 of the phase structure

Recent review:  
 A. Andronic, et al, NP A772,  
 167(06)



# Fundamental Scientific Issues

---

## Future Facilities



### What is the QCD phase structure?

- QCD phase boundary, critical point, Quarkyonic matter, Glueball,

...

**ALICE at LHC:**  $\mu_B = 0$  region. Initial temperature and thermalization.

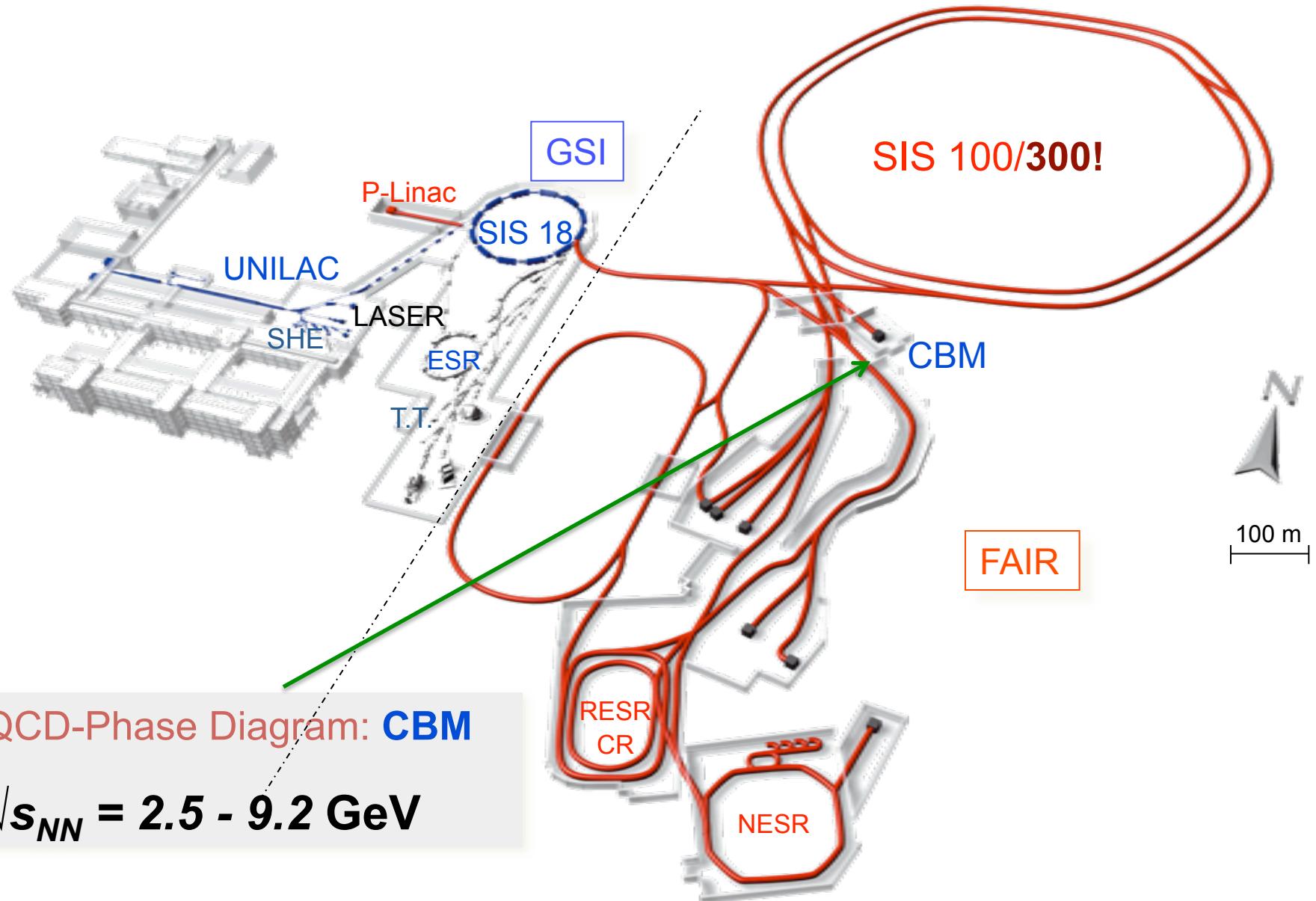
**BES at RHIC:** Phase-I data analysis in progress. Phase-II in 2014.

**SHINE at SPS:** Light heavy ion collision data analysis in progress.

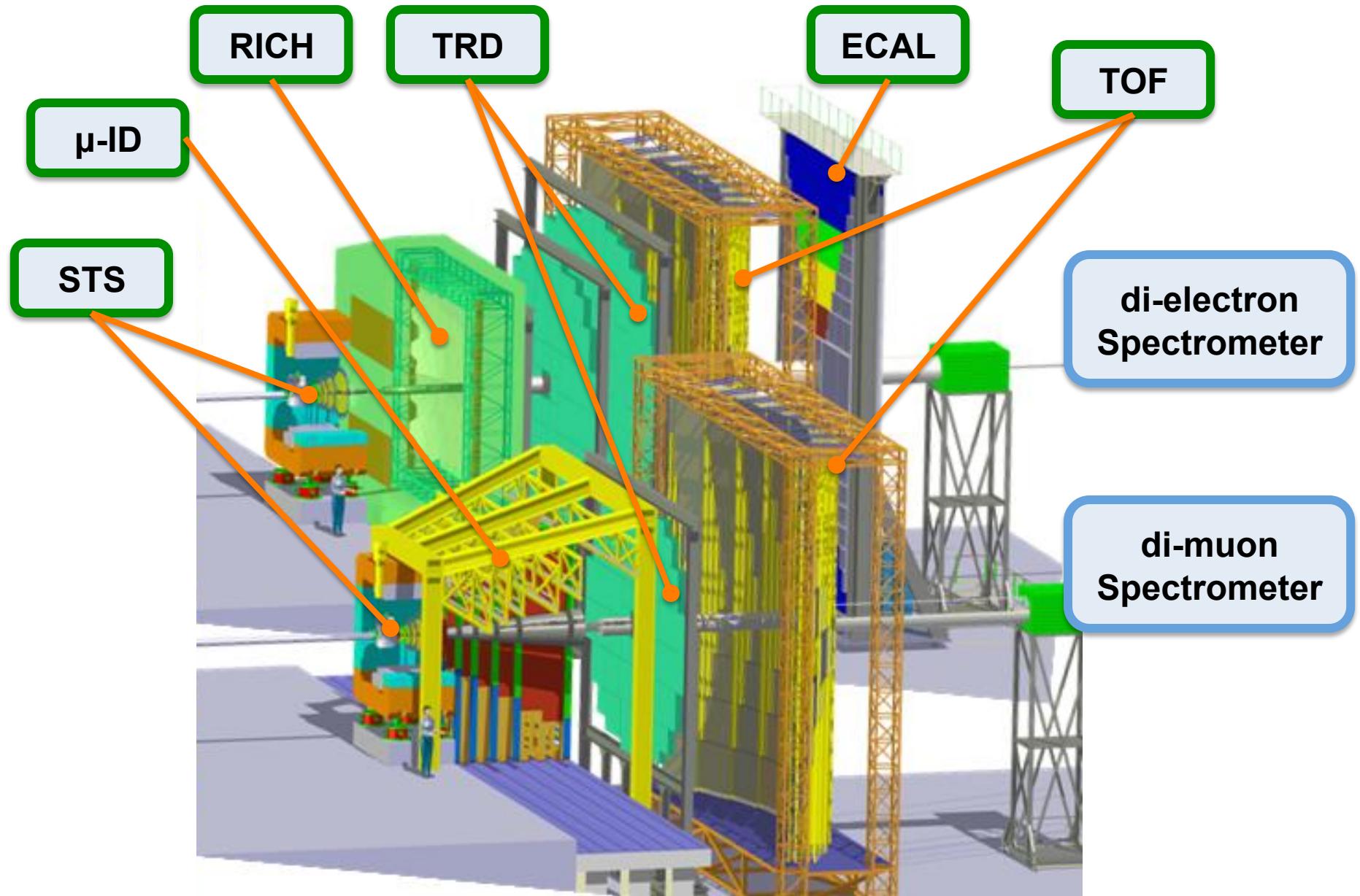
**MPD at NICA:** 2015.

**CBM at FAIR:** 2018. Study the detailed/rich phase structure, high luminosity necessary. **SIS300 is essential!**

# Facility for Antiproton and Ion Research



# CBM at FAIR (2018 data taking starts)



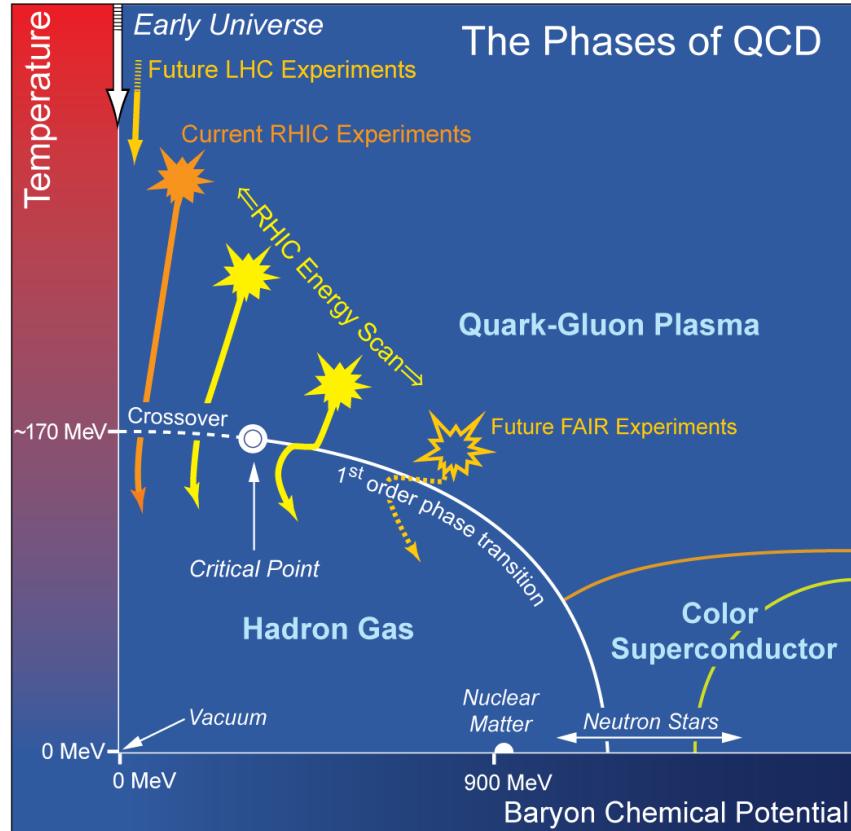
Next five-year, a full-time job for Peter:  
**Transfer the CBM dream to a  
world-class detector!**

**Best wishes** and



**Happy Birthday!**

# The QCD Critical Point



- LGT prediction on the transition temperature  $T_c$  is robust.
- LGT calculation, universality, and models hinted the existence of the critical point on the QCD phase diagram\* at finite baryon chemical potential.
- Experimental evidence for either the critical point or 1<sup>st</sup> order transition is important for our knowledge of the QCD phase diagram\*.

\* *Thermalization has been assumed*

M. Stephanov, K. Rajagopal, and E. Shuryak, PRL **81**, 4816(98); K. Rajagopal, PR **D61**, 105017 (00)

<http://www.er.doe.gov/np/nsac/docs/Nuclear-Science.Low-Res.pdf>